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Carbon Monoxide Exposure in Mountaineers on Denali

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ABSTRACT

Carbon monoxide (CO) poisoning is a particular hazard for persons camping in cold, stormy, high altitude locations such as Mt. McKinley (Denali). Recently, two climbers were killed by CO on Denali while cooking in a tightly sealed tent. CO has also contributed to high altitude illness. To assess exposure in various shelters we measured CO levels with a portable monitor in a mountaineering tent, igloos and snow caves during an ascent of Denali.

Concentrations measured at altitudes between 2000 and 5200m usually exceeded the U.S. Environmental Protection Agency's 1-hour standard of 35ppm, reaching a mean value as high as 165ppm in a snow cave. Based on the data from this preliminary study, the use of a larger vent hole, approximately the size of a ski pole basket, appears to provide enough ventilation to maintain CO levels at more acceptable levels in snow caves and igloos.

INTRODUCTION

Ever since the early polar explorers began using portable kerosene stoves to cook and melt snow for water, numerous accounts of people being poisoned by the exhaust gases from such stoves have been published (1-3). One such account comes from the journey of Stefansson to the North Pole. He reported that while using a Primus stove (a small kerosene stove) in a snow house, the walls "became iced and impervious to gases," whereupon two of his companions collapsed in the house while he and the fourth member of the party managed to extinguish the stove and escape before collapsing: "An hour later three of the party members were well enough to go into the house again..." (1).

In the modern era, we have the advantage of considerable research on topics such as emission rates of carbon monoxide (CO) from stoves and lanterns (2,4), the concentrations of CO that can be found in tents and snow houses (1-5), and the amount of carboxyhemoglobin (COHb) found in the blood after carbon monoxide exposure (3). The acute health effects of exposure to carbon monoxide are well established (6). Most recently, Cohen (4), using a combination of laboratory work and computer modeling predicted that high levels of CO could be attained in tents when a cooking stove was used even for periods less than 30 minutes if ventilation were inadequate.

Despite considerable knowledge in this area, morbidity and mortality from CO poisoning persists on Mt. McKinley (Denali). In 1986, two Swiss climbers died on Denali while cooking in a tightly sealed tent at 4400m, ironically, only a few meters from the medical research camp. The purpose of this study was to better define the exposure to CO on Denali under typical mountaineering conditions in typical shelters and to test various methods of reducing the hazard by changing shelter ventilation.

Measurements were made during and after the use of the stove for meal preparation. The data indicate that CO exposure may reach toxic levels in all types of shelter and that adequate ventilation in snow shelters can be established by larger vent holes.

METHODS

Two of the authors (WT and SM) made the measurements during a climb of Denali in June of 1985. Measurements were made in three types of shelters used for mountaineering: tent, igloo, and snow cave (Figure 1). Because climbers often encounter temperatures well below freezing and strong winds, these shelters are designed to be small in volume and to have low ventilation rates. The tent was nylon, designed for two persons, with double-wall construction and a vestibule for cooking that was open to the inside of the tent. Igloos were made with cut snow blocks, and the cooking and sleeping level was higher than the entrance. Snow caves were also constructed with the living area higher than the entrance to help maintain warmth.

Carbon monoxide (CO) measurements were made using a calibrated CO monitor (Gas Tech Portable, Model CO-82). The instrument was zeroed before and after each series of measurements. A calibration standard of 180ppm CO was used at 90m, 2600m, 3400m, and 4300m above sea level to define a relationship be-

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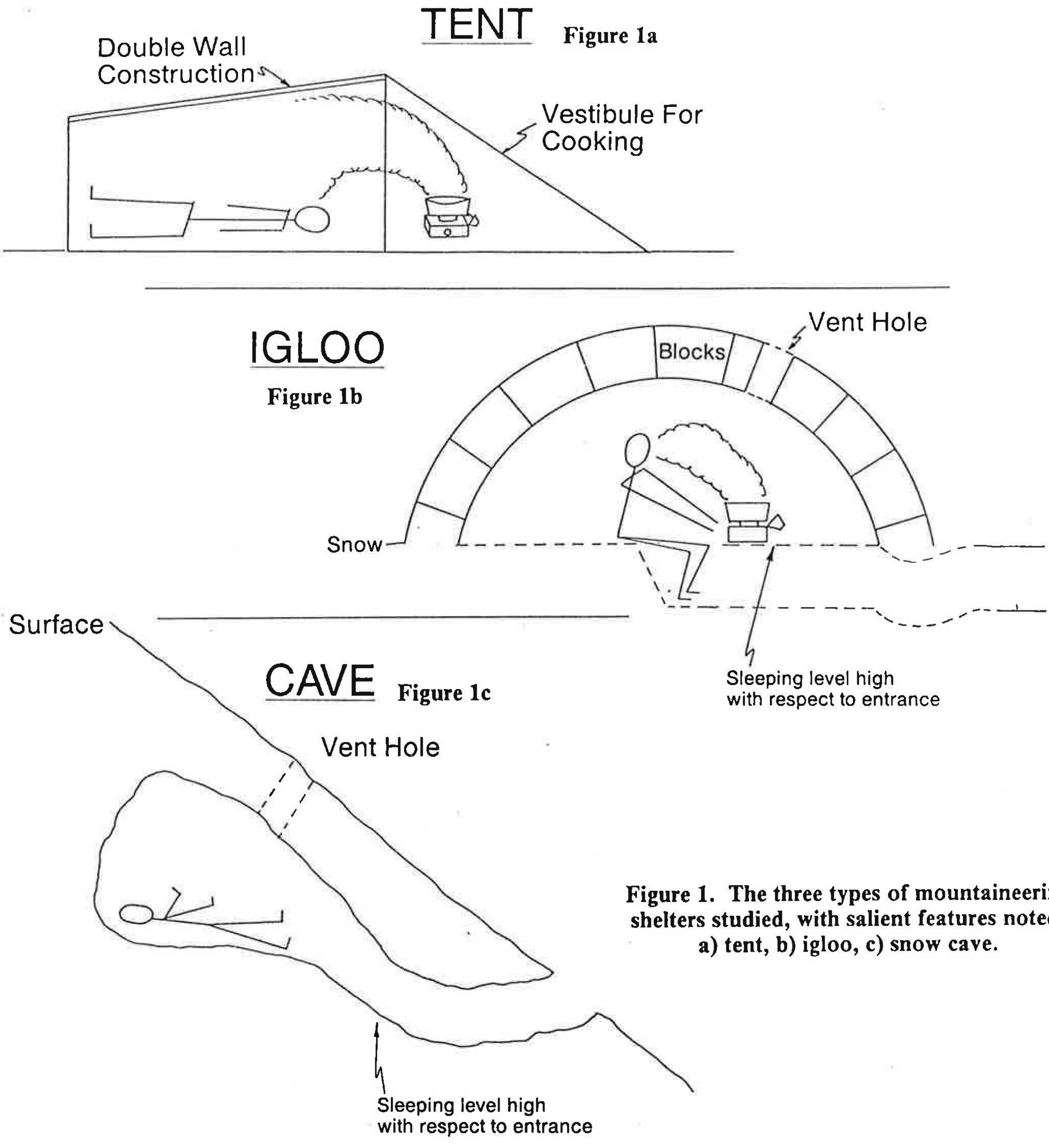

Figure 1. The three types of mountaineering shelters studied, with salient features noted: a) tent, b) igloo, c) snow cave.

tween the instrument's response to the standard and the altitude. When plotted, an altitude correction function was derived and applied to the data. (The instrument reads low at high altitude due to decreased partial pressure of gas.) This was preferred over adjusting the instrument at each altitude. Readings of the CO instrument were recorded at approximately 10-minute intervals during monitoring.

Three different stoves with similar fuel consumption rates were used during the testing. These were an Optimus 111B, an Optimus 8R, and a MSR Firefly. All stoves burned white gas and were in good operating condition. None had special jets for high altitude, and no attempts were made to alter the air/fuel ratios. The maximum fuel consumption rate for two of the three stoves (111B and 8R) has been measured to be approximately 210 grams/hour and is estimated to be less for the Firefly.

Measurements were made during the preparation of the meals in each of the dwellings. These periods typically lasted between one and two hours and consumed 150–300 grams of fuel. The detector was located in the breathing zone of the occupants, approximately 1.5 to 2 meters horizontally from the cookstove and approximately 1 meter vertically, depending on the particular shelter. Efforts were made to standardize this sampling location. CO measurements were also made after the stove was turned off to calculate ventilation rates. Assuming exponential decay, the ventilation rate (air exchange rate of the dwelling) is the slope of the logarithm of CO concentration plotted against time. A more in-depth study of this method and its assumptions can be found in American Society of Testing and Materials (ASTM) (7). In snow caves, all measurements were repeated with different sized ventilation holes. Ventilation area was changed in the tent by partially opening or closing the zippered door. The reported CO concentrations have been corrected for altitude.

RESULTS

Tent

Table 1 gives the data that was taken inside the tent at 2300m using the 111B stove. During the last two runs, the CO concentrations were notably higher than the first two runs and were above the toxic level (50ppm). The outdoor wind speed during the first run was 7m/s, while there was no detectable wind during the following measurements. This explains the high ventilation rate in run 1 as measured by CO decay rate.

Igloo

The results from using the 111B and 8R stoves in the igloos at 2600 and 4300m are presented in Table 2. CO reached toxic levels in all tests when the stoves were burning for more than fifteen minutes. The first test was made while the snow blocks were still fresh and porous, which may have led to the relatively high air ventilation rate (air exchange rate) observed. The last three runs were made in igloos that had relatively less permeable walls due to glazing and accumulated snowpack. There was a decrease in ventilation rate for the later tests.

Snow Cave

Table 3 summarizes the results for the snow caves at 5000 and 5300m using the 8R and MSR stoves. While in these snow caves, the highest CO concentration was recorded (190ppm). Therefore, we investigated the relationship between concentration and the vent size.

Vent Area Versus Ventilation Rate

In a snow cave, vent holes of different sizes were made to test the relationship between air exchange rate and the size of the hole. The size of the vent area does not include the opening at the cave entrance, since the floor of the cave is higher than the entrance. Three basic sizes were tested: an ice axe shaft hole (approximately $10cm^2$), a ski basket hole (approximately $50cm^2$), and a hole made with the handle of a shovel (approximately $80cm^2$). The relationship between vent area and the ven-

Table 1

	TENT			
Stove Type	111B	111B	111B	111B
Altitude (meters)	2300	2300	2300	2300
Delta temp. (degrees C)	11	6	8	6
Wind Speed (m/s)	7	none	none	none
Burn Time (hrs)	.75	.5	.5	.5
CO conc (ppm)				
# Points	10	5	6	6
Max.	40	40	80	110
Mean	25	35	50	70
Min.	15	25	15	55
Gross Ventilation (cm^2)	4500	19400	2600	19400
Ventilation Rate (air exchange/hr)	150	65	13	38
# of points in decay curve	3	15	10	9

tilation (air exchange) rate is shown in Figure 2. In this limited data set the ventilation rate closely correlates with the gross vent area (R^2=0.903). A hole of 50cm^2 more than doubled the ventilation rate, and also kept CO concentrations below the EPA standard of 35ppm for one hour.

Air Exchange Versus Dwelling Type

Air exchange rates in the three shelters were determined by decay of CO over time with the source off. Figure 3 shows typical decay rates for the tent, the igloos, and the snow caves with holes. For the tent, the entrance door was half open. Even without perceptible wind, the ventilation rate was calculated at 65 air exchanges/hr (ACH). The inside vs outside temperature difference was about 6°C. CO concentrations reached background ambient values in three minutes. For the igloo, with a vent hole of approximately 45cm^2, a typical air exchange rate was five air changes/hour, and the CO concentration had not reached ambient levels after 30 minutes. For the cave with a vent hole of approximately 20cm^2, a typical air exchange rate was 3.6 air changes/hour, and after 45 minutes the CO concentration was still relatively high.

DISCUSSION

The observations and experiments performed on Denali between 2000m and 5200m were made under typical snow camping conditions. The stoves and shelters are all common to mountaineering. The snow burn

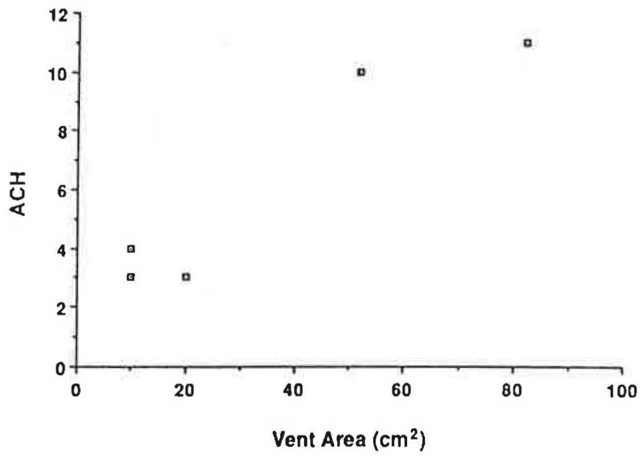

Figure 2. Air exchange rate (ACH) vs. size of vent area in a snow cave. A vent greater than 50 cm sq resulted in higher exchange rates.

times were actual meal or water preparation times required to support two or three climbers. It is important to note that 8 of the 13 sets of measurements of CO exceeded 50ppm during stove use. Our data, though limited, indicate that mountain climbers on Denali who cook in shelters may be at risk of acute carbon monoxide poisoning and that increasing shelter ventilation effectively reduces the risk.

Average CO concentration ranged from 15ppm to 165 ppm, varying primarily with shelter ventilation rates but also with fuel consumption and stove type. The air

Table 2

IGLOO				
Stove Type	111B	111B	8R	8R
Altitude (meters)	2600	4300	4300	4300
Delta temp. (degrees C)	17	23	23	23
Wind Speed (m/s)				
Burn Time (hrs)	1	1	.5	.25
CO conc (ppm)				
# Points	8	14	5	4
Max.	85	140	80	40
Mean	80	120	70	35
Min.	70	80	60	30
Gross Ventilation (cm^2)	none porous	45 glazed walls	45 glazed walls	45 glazed walls
Ventilation Rate (air exchange/hr)	13	5	4	14
# of points in decay curve	17	22	10	10

exchange rates were determined to be lowest in igloos and snow caves where the walls are more impervious to air flow and ventilation holes limited. We confirmed similar CO levels and ventilation rates during March 1986 in snow caves at 1000m and 1500m in the Presidential Range of the White Mountains of New Hampshire (unpublished observation).

The plot of the CO concentration decay suggests that the mechanism for ventilation in the snow caves and igloos is relatively similar, while the tent may differ. Wind is one factor expected to exert much more influence on ventilation in a tent compared to snow shelters, especially once an interior ice-glazed surface is formed. It should be noted that during the first experimental run inside of the tent, a wind of approximately 7m/s was blowing outside. This run resulted in an air exchange value of 150 per hour. Subsequent measurements were in calm conditions, and air exchange rates were closer to the other two shelters but still generally higher for the tent. The much larger vent area of the tent appears to be a distinct advantage. It should be noted that tightly sealed tents, however, could also form an ice glazed interior surface in the absence of wind or be covered with snow on the outside; even tents have the potential for low air exchange rates, as demonstrated by the recent deaths on Denali.

The effectiveness of using larger vent holes in snow caves is an important finding. We found the relationship between the air exchange rate in the snow cave and the vent area was relatively linear, implying only a small contribution to the ventilation rate was made by dif-

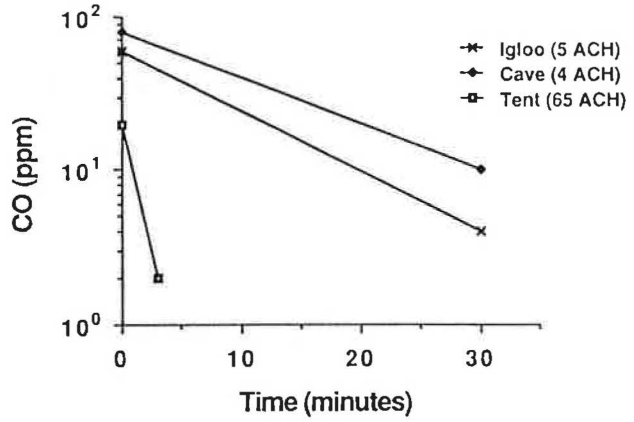

Figure 3. Carbon monoxide concentration in parts per million over time for the three different shelters. The shelter with high air exchange rate (ACH) had the most rapid decline in CO after the stove was turned off.

fusion of air through the semi-porous snow and ice. In order to make a rough estimate as to what vent size would be required to keep the CO concentration below a certain level, the CO concentration was also plotted against the vent size. We recommend a minimum of $50cm^2$ vent in a snow cave, which seems to be adequate even if the snow walls are glazed.

The emission rate (or source strength) of the cooking stove also influenced the level of CO. Based on fuel consumption rates determined for the 111B and 8R and boiling times for all three stoves, it appeared that the MSR Firefly had a lower fuel consumption rate and

Table 3

SNOW CAVE					
Stove Type	8R	8R	MSR	MSR	8R
Altitude (meters)	5000	5000	5000	5300	5300
Delta temp. (degrees C)	8	11	14	11	5
Wind Speed (m/s)					
Burn Time (hrs)	1 hr.	1	2	1	.25
CO conc (ppm)					
# Points	10	6	11	4	3
Max.	190	35	95	65	30
Mean	165	30	70	50	28
Min.	70	25	60	38	25
Gross Ventilation (cm^2)	11	52	20	11	81
Ventilation Rate (air exchange/hr)	4	10	3	3	11
# of points in decay curve	18	4	6	11	5

thus possibly a lower emission rate.

The concentrations of CO recorded in the various shelters are high enough to produce significant toxicity. Of the 13 total experiments, eight showed mean concentrations of 50ppm or higher. Fifty ppm CO results in a carboxyhemoglobin level of about 8%, assuming the kinetics of uptake and equilibration remained the same as sea level. There is some evidence, however, that CO uptake is increased because of the hyperventilation induced by the hypoxia of high altitude (8,9). Although 8% COHb is not considered toxic at sea level, such a level will exacerbate the altitude hypoxia. The normal arterial oxygen saturation (SaO2%) of a climber on Denali after two days acclimatization to 4400m is 80%. A decrease in oxygen carrying capacity of 8% to an effective SaO2% of 72% due to COHb would result in a very significant drop in oxygen transport, rendering the climber at a "physiologically" higher altitude and could easily precipitate acute mountain sickness. In 1985, two Denali climbers required rescue because of severe acute mountain sickness induced by CO exposure (10). Low-level CO exposure may thus contribute to altitude illness. Further evidence for an additive effect of CO and altitude hypoxia was a study by Vollmer *et al.* (11). Four of seventeen healthy subjects at a simulated altitude of 4725m collapsed when COHb reached 9% to 19% (9), values not associated with collapse at sea-level. The EPA has more recently reviewed the combined effects of CO and altitude (12).

The higher CO concentrations recorded in our study are clearly in the range to cause CO toxicity, depending mostly on the exposure time. Symptoms of CO poisoning are identical to those of acute mountain sickness; i.e., headache, nausea, dizziness and lassitude. Therefore, differentiating the two may be impossible. Also, because of the lower inspired oxygen pressure, the rate of elimination of CO from hemoglobin may be impaired.

Two climbers found dead of CO poisoning from cooking in a tightly sealed tent on Denali in 1986 had COHb levels of 65.6% and 56.9% at autopsy, levels considered lethal even at sea level. Although the interactions of CO and altitude hypoxia need further investigation, it is clear that CO poisoning poses a serious risk when using stoves in shelters at high altitudes.

SPECIFIC RECOMMENDATIONS

As a result of the measurements obtained, the authors recommend that tents, igloos and snow caves always be vented when combustion appliances are used. We suggest that mountaineers adopt the practice of creating a vent hole in igloos and snow caves that is at least the diameter of a ski pole basket whenever a stove is in use, especially at high altitude. This vent should be located in the vicinity of stove operation and as high as possible in the dwelling. To maintain vital warmth offered by the shelter without risk of physical impairment from CO poisoning, the vent hole may be plugged with snow after finishing use of the stove. Using this method, the authors on this McKinley climb were able to maintain temperature within properly constructed igloos and caves in the range of 15 to 20°C above ambient except when the vent was open.

In light of the recent mountaineering deaths and illness attributable to CO poisoning and increasing activity of high altitude mountaineering, further research is needed in this area. Altitudes above 4000m are sufficiently hostile without the added danger of carbon monoxide.

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